

FINAL TASK REPORT

Instructions: Provide all information identified below for the duration of this project. List "Research Objectives" in bullet format. Provide "Summary of Research" in narrative format.

Research Title: Gravity Wave Modeling and Airglow Applications

Principal Investigator: David C. Fritts

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Research Objectives:

- examine the dynamics and instability processes accompanying gravity wave breaking
- examine the transition to turbulence in stratified and sheared flows
- examine airglow responses to wave and instability processes near the mesopause

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REPORT DOCUMENTATION PAGE

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| 6. AUTHOR(S) David C. Fritts | | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Northwest Research Associates/CoRA Division P.O. Box 3027 Bellevue, WA 98009-3027 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM Air Force Office of Scientific Research 110 Duncan Ave., Suite B115 Bolling AFB, D.C. 20332-8050 | | | | 10. SPONSORING / MONITORING AGENCY REPORT NUMBER | |
| 11. SUPPLEMENTARY NOTES | | | | | |
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| 13. ABSTRACT (Maximum 200 Words) This AASERT supplemental grant supported numerical, theoretical, and observational studies of gravity wave and shear instability processes in the atmosphere and their impact on airglow layers near the mesopause. Efforts during the past year have explored new ground in vortex dynamics, extended our numerical studies toward both wave breaking and shear instability dynamics, and addressed the completion of a number of papers initiated under this AFOSR grant. Collectively, this grant has contributed enormously to our understanding of a diversity of wave and shear instability processes, the transition to turbulence in such flows, the dynamics of vorticity and turbulence, and applications to atmospheric measurements. Our studies have defined what we believe to be the important dynamics accompanying the transition to turbulence in a breaking wave, the dynamics of a vortex pair evolving in mean shear and stratification in two and three dimensions, and the implications of a variable wind environment for gravity waves observed in mesospheric airglow. More recent efforts have addressed the dynamics of twist waves and spanwise-varying vortex sheets as well as very-high-resolution KH shear instability dynamics. Interesting implications include significant anisotropy in turbulence and mixing relative to expectations of turbulence theory applied to such flows. | | | | | |
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Funding Summary (\$K): FY97 - 99

| In House | Capital Equip. (> \$5,000 each) | Subcontractor | Total |
|----------|------------------------------------|---------------|-----------|
| 114,189 | | | \$114,189 |

Summary of Progress:

see attached

Summary of Research Results:

This project has contributed a number of significant results to date. Our more recent wave breaking studies (Andreassen et al., 1998, Fritts et al., 1998, see below) have shown that vorticity dynamics does provide a useful and insightful view of the transition from two-dimensional (2D) laminar to three-dimensional (3D) turbulent flows. Indeed, these numerical results have stimulated an analytic description of the twist wave vortex dynamics accounting for the transition to, and the enstrophy cascade within, a turbulent motion field (Arendt et al., 1998, see below). The result is a new and much more quantitative understanding of turbulence dynamics than was previously available.

The same approach by Jim Garten, a graduate student then postdoc in our group, led to a similarly insightful description of the evolution of paired, counter-rotating vortices in stratified and sheared flows. These studies are relevant both to the evolution and stability of aircraft vortices at larger scales and to turbulent dynamics within the inertial range of turbulence at smaller scales of motion. Results to date have illustrated the manner in which enstrophy is transferred to smaller scales via flow instability and baroclinic tendencies. A second student, Mike Gourlay, likewise employed vortex dynamics to examine the evolution of the vortex sheets arising in such sheared and stratified flows in association with the initial flow instabilities. In both the wave breaking and shear flows we have performed to date, the evolution of intensifying vortex sheets has played a central role, and we expect that these dynamics also are key to understanding the flow of energy and enstrophy to smaller scales within the turbulence spectrum. A third student, Teresa Palmer, is pursuing very high resolution KH breakdown in 3D in order to address turbulence generation and restratification in the stratosphere in support of the Airborne Laser (ABL) program. These studies are yielding the highest resolution (and least viscous) descriptions of KH dynamics to date and will be key to understanding laser propagation through highly refractive structures arising from shear-generated turbulence. Finally, we have also used linear gravity wave theory to examine the propagation of gravity waves in variable environments in which the vertical structure of short horizontal-scale waves is dictated by the vertical profile of the local mean wind. These results have been used to interpret airglow imager and MF radar measurements of wave structure and mean winds during the ALOHA-93 campaign in order to assess the propagation character of such motions. This study suggests that many of the short horizontal-scale wave structures observed at mesopause altitudes are ducted responses to the variable winds imposed by low-frequency motions at these altitudes. Assuming these results hold in general, the implications for wave forcing and effects at mesopause altitudes are significant. First, one must be cautious in the inference of wave forcing assuming all waves are vertically propagating, as they clearly are not. And second, not all of the motions seen to have large signatures at airglow altitudes can be expected to have significant atmospheric influences.

Progress during the past year has occurred in several areas. We completed revision and editing of three papers describing the instability and transition to turbulence in a breaking wave. These results have now appeared or are in press in the Journal of Fluid Mechanics and the Proceedings of the European Geophysical Society (see publications). We have evaluated the dominant mechanisms (Mike Gourlay, graduate student, now a postdoc) as they arise in more general flows, via posing of the problem separately from the parent instability process. We have also explored the extent to which the same dynamics appear to account for the turbulence transition and cascade in shear flow (KH) instability (Teresa Palmer). Initial results from these efforts are very promising and suggest that the indications of our earlier studies were correct: there is a general class of instabilities and interactions which initiate and drive the turbulence cascade in a variety of transitional flows. A third graduate student (then postdoc) (Jim Garten) examined the two-dimensional dynamics of paired vortices in shear and stratification as a part of his Ph.D. thesis, which he completed and defended in November 1997. Our final effort relevant to this AASERT research was the application of gravity wave theory to understand the nature of small-scale wave structure in mesospheric airglow layers. This appeared in a special issue of the Journal of Geophysical Research in November 1997.

Appendix A: In-house Activities

Instructions: Provide all information identified below for the duration of this project. "Personnel" should include each scientist or engineer who contributed to the research during the year. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort. Honors may include recognition both inside and outside the academic and Air Force science & technology (S&T) communities. Extended scientific visits may include collaboration with other research programs, both foreign and US.

Personnel (all Univ. of Colorado staff or students):

| | <u>Name</u> | <u>Degree</u> | <u>Discipline</u> | <u>Involvement</u> |
|---------------------|-----------------|---------------|-------------------|--------------------|
| In House Employees | David C. Fritts | Ph.D. | Physicist | 0mo/yr |
| | Jim Garten | Ph.D.(compl.) | Physicist | 1/3time |
| | Mike Gourlay | Ph.D.(compl.) | Physicist | 1/3 time |
| | Teresa Palmer | Ph.D.student | Physicist | 1/3 time |
| On-site Contractors | | | | |
| Visitors | | | | |

Publications Citing this AASERT Supplemental Support

- Andreassen, Ø., P. Ø. Hvidsten, D. C. Fritts, and S. Arendt, 1998: Vorticity dynamics in a breaking gravity wave, 1. Initial instability evolution, *J. Fluid Mech.*, **367**, 27-46.
- Fritts, D. C., S. Arendt, and Ø. Andreassen, 1998: Vorticity dynamics in a breaking internal gravity wave, 2. Vortex interactions and transition to turbulence, *J. Fluid Mech.* **367**, 47-65.
- Isler, J. R., M. J. Taylor, and D. C. Fritts, 1997: Observational evidence of wave ducting and evanescence in the mesosphere, *J. Geophys. Res.*, **102**, 26,301-26,313.
- Garten, J. F., S. Arendt, D. C. Fritts, and J. Werne, 1998: Dynamics of counter-rotating vortex pairs in stratified and sheared environments, *J. Fluid Mech.*, **361**, 189-236.
- Arendt, S., D. C. Fritts, and Ø. Andreassen, 1998: Kelvin twist waves in the transition to turbulence, in *Dynamics and Statistics of Concentrated Vortices in Turbulent Flows*, Euro. J. Mech. B/Fluids, **17**, 595-604.

Gourlay, M. J., 1999: Stability and Dynamics of Stretched Fluid Shear Layers, Ph.D. thesis, University of Colorado, Department of Physics.

Gourlay, M. J., S. C. Arendt, D. C. Fritts, and J. Werne, 1999: Stability and dynamics of shear layers with periodic spanwise variation, *J. Fluid Mech.*, submitted.

Technical Presentations:

- Garten, J.F., D.C. Fritts, and Ø. Andreassen, Simulations of a vortex pair in sheared and stratified environments, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Fritts, D.C., S. Arendt, and Ø. Andreassen, Vorticity dynamics in a breaking gravity wave, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Palmer, T.L., D.C. Fritts, and Ø. Andreassen, Three dimensional simulations of Kelvin-Helmholtz billows and secondary instabilities, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Fritts, D.C., Modeling of wave and instability processes in the middle atmosphere, CEDAR Prize Lecture, CEDAR Summer Symposium, Boulder, June 1995.
- Palmer, T.L., D.C. Fritts, and Ø. Andreassen, Two and three-dimensional simulations of Kelvin-Helmholtz billows and secondary instabilities, Int'l. Union of Geodesy and Geophysics General Assembly, Boulder, July 1995.
- Arendt, S., D.C. Fritts, and Ø. Andreassen, Dynamics of Kelvin waves on vortex tubes, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.
- Arendt, S., D.C. Fritts, and Ø. Andreassen, Vortex tube evolution in a breaking gravity wave, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.
- Gourlay, M.J., D.C. Fritts, S. Arendt, and Ø. Andreassen, Instability and evolution of finite span vortex sheets, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.
- Garten, J.F., D.C. Fritts, S. Arendt, and Ø. Andreassen, Counter-rotating vortex tubes in a stably stratified fluid, 21st EGS Symposium on Vortex Dynamics, The Hague, May, 1996.
- Andreassen, Ø., S. Arendt, and D.C. Fritts, Formation of vortices and potential vorticity in the field of a breaking wave, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

- Palmer, T.L., D.C. Fritts, and Ø. Andreassen, Secondary instability, breakdown, and restratification of Kelvin-Helmholtz billows at high Reynolds numbers, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.
- Garten, J.F., D.C. Fritts, and S. Arendt, Dynamics of counter-rotating vortices in stratification and shear, annual APS meeting, November 1996.
- Arendt, S., D.C. Fritts, and Ø. Andreassen, Kelvin twist waves due to a breaking gravity wave, annual APS meeting, November 1996.
- Arendt, S., D.C. Fritts, and Ø. Andreassen, Kelvin twist waves in the transition to turbulence, Euromech Symposium, Marsellies, June 1997.
- Fritts, D.C., Gravity wave breaking: Instability dynamics and transition to turbulence, Int'l. Symp. on the Dynamics of the Mesopause Region, Kyoto, March. 1998.
- Garten, J. F., J. Werne, D. C. Fritts, and S. Arendt, The effects of ambient stratification on the Crow instability and subsequent vortex reconnection, Europ. Mech. Symposium on Vortex Dynamics, Toulouse, August, 1998.
- Fritts, D. C., Instability dynamics and mixing due to gravity waves in the lower and middle atmosphere, AGU Chapman Conf. on Atmospheric Science Across the Stratopause, Annapolis, April, 1999.
- Gibson-Wilde, D. E., D. M. Riggan, D. C. Fritts, J. Werne, and R. J. Hill, Small-scale dynamics in the stratopause region, AGU Chapman Conf. on Atmospheric Science Across the Stratopause, Annapolis, April, 1999.
- Werne, J., and D. C. Fritts, Turbulence and mixing in a stratified shear layer: 3D KH simulations at $Re = 24,000$, Europ. Geophys. Society, April, 1999.
- Werne, J., and D. C. Fritts, Anisotropy in stratified shear turbulence, DOD HPCMO User Group, June, 1999.
- Fritts, D. C., and J. Werne, Turbulence and mixing due to KH instability: Implications for layering and atmospheric structure, IUGG Gen. Assem., Birmingham, July, 1999.
- Fritts, D. C., J. Werne, and T. L. Palmer, The dynamics of turbulence accompanying KH instability, IUGG Gen. Assem., Birmingham, July, 1999.
- Fritts, D. C., and J. Werne, Turbulent mixing and dissipation accompanying KH instability, IUGG Gen. Assem., Birmingham, July, 1999.
- Fritts, D. C., and J. Werne, Dynamics and mixing due to KH shear instability at high Reynolds numbers, NCAR Geophys. Turbulence Program Workshop on Mixing and Reactive Species, Boulder, July, 1999.
- Fritts, D. C., J. A. Werne, D. E. Gibson-Wilde, and R. J. Hill, Simulations of KH instability and implications for radar measurements and inferences of atmospheric dynamics, Int'l. Workshop on Radio Methods for Studying Turbulence, Urbana, August, 1999.

Invention Disclosures and Patents Granted: None

Invited Lectures, Presentations, Talks, etc.:

Invited Speaker, Int'l Workshop on Atmospheric Waves, Adelaide, September 1997.

Invited Speaker, Int'l. Sym. On the Dynamics of the Mesopause Region, Kyoto, March 1998.

Invited Speaker, AGU Chapman Conf. on Atmospheric Science Across the Stratopause, Annapolis, April, 1999.

Invited Speaker, Symp. on Layered Phenomena, IUGG Gen. Assem., Birmingham, July, 1999.

Invited Speaker, NCAR Geophys. Turbulence Program Workshop on Mixing and Reactive Species, Boulder, July, 1999.

Professional Activities (editorships, conference and society committees, etc.):

CADRE (Coupling And Dynamics of Regions Equatorial) measurement campaign coordinator and Guest Editor of JGR Special Issue (Nov. 1997), 1993 - 1997.

Convenor and Session Chairman, IUGG Symposium, Uppsala August 1997.

Convenor and Session Chairman, Int'l. Sym. On the Dynamics of the Mesopause Region, Kyoto, March 1998.

Convenor and Session Chairman, IUGG Symp., Birmingham, July, 1999.

President, International Commission on the Middle Atmosphere (ICMA), 1995 - 1999.

Honors Received (include lifetime honors such as Fellow, honorary doctorates, etc., stating year elected):

CEDAR Prize Lecturer, Summer CEDAR Symposium, June 1995.

Extended Scientific Visits From and To Other Laboratories:

Visiting Professor with the Radio Atmospheric Science Center, Kyoto University, Kyoto, Japan, September - December 1996.

Appendix B: Off-Site Contract and Grant Activities

Instructions: Provide all information identified below for the last FY only. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort.

Publications: N/A

Appendix C: Technology Transitions/Transfers Detailed Listing

Tech transfers:

In association with this grant and using funding in place through colleagues at the Norwegian Defence Research Establishment, we have contributed to the development of a high-level graphics package for visualization of three-dimensional data sets in order to assist with our understanding of the complex flows accompanying transitions to turbulence. This package also appears to be potentially beneficial to other communities, particularly medical imaging and oil and gas exploration. Hence, it is now widely available via distribution on the Web and installation at the DoD Major Shared Resource Centers. It is also available to potential commercial customers, should such interest arise.